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SUMMARY

A study was conducted to determine the effectiveness of seven landing approach methods using current separation intervals, and in combination with reduced separation intervals. It was determined that of the seven methods studied, only the dual-path and dual-path-curved methods provided significant benefits over the current method when the current separation intervals were used. With all the methods, it was found that the landing operations decreased as the proportion of heavy aircraft in the landing mix increased.

Reducing the current separation intervals to 5.56 km (3 n. mi.) for large aircraft following heavy aircraft was not particularly advantageous for any method in the range of typical landing mixes. Reducing the current intervals to 3.70 km (2 n. mi.), however, increased the landing capacity by 65 percent for the current method in the range of typical mixes of aircraft. With either of the reduced intervals, there was also a beneficial trend toward increasing landing capacities with increasing proportions of heavy aircraft.

When the large gains resulting from a reduction in the separation interval to 3.70 km (2 n. mi.) were combined with the gains from the vortex avoidance geometry provided by the dual-path and dual-path-curved methods, the landing capacity at a typical current landing mix was approximately double that for the current method. This gain increased as the proportion of heavy aircraft in the mix increased.

The results also showed that for every method studied, the passenger delivery capacity was increased by an increase in the proportion of heavy (high passenger capacity) aircraft in the mix. These results indicate that an increased demand for air travel will probably require not only advanced approach methods and large reductions in separation intervals, but an increase in the proportion of high passenger capacity aircraft as well.

INTRODUCTION

Projected passenger enplanements for the remainder of the century will require increased capacity in the air transportation system. Many airports are currently saturated for long periods of the day, and more airport saturation is expected as the demand for air transportation grows.

Two promising techniques for meeting this anticipated demand are the development of advanced landing approach methods and the reduction of the separation intervals currently required between approaching aircraft. Data in references 1 and 2 indicate that the microwave landing system (MLS) has the potential to allow landing approaches using multiple path and curved methods. Reductions in separation intervals may also become feasible (refs. 3 to 5) as advanced air

traffic control systems and wake turbulence avoidance and attenuation research continues.

This report presents the results of a study of the potential gains in landing capacity offered by seven different approach methods. The results of the various methods are presented first for the current separation intervals, and then for these methods in combination with reduced intervals. Some discussion of the effects of aircraft size on the passenger delivery capacity is also included. The study is limited to current commercial jet transport aircraft landing on a single runway.

SYMBOLS AND ABBREVIATIONS

Values are given in SI and U.S. Customary Units. Measurements were taken in U.S. Customary Units.

a	acceleration, m/sec^2 (ft/sec^2)
DOT	Department of Transportation
h	vertical separation distance, m (ft)
ILS	instrument landing system
i	designates leading aircraft in a pair
IFR	Instrument Flight Rules
j	designates following aircraft in a pair
MLS	microwave landing system
NASA	National Aeronautics and Space Administration
P	proportions of aircraft of a certain type in a mix of aircraft
p_{ij}	probability of pair combination i-j
t	time, sec
$\bar{t}$	mean interarrival time, sec
t_{ij}	interarrival time between aircraft i and j at runway, sec
V	velocity, knots
x	longitudinal distance between projected touchdown point and a point on extended runway center line, km (n. mi.) or m (ft)
x'	longitudinal distance between two projected touchdown points, m (ft)

γ length of approach path between projected touchdown point and ILS gate, km (n. mi.)

Δ horizontal separation interval, km (n. mi.)

δ_{ij} wake turbulence separation interval between aircraft i and j, km (n. mi.)

θ angle of approach path, deg

λ landing capacity, operations/hr

μ passenger delivery capacity, passengers/hr

ξ passenger capacity of an aircraft at a passenger load factor of 65 percent

Subscripts:

A type A aircraft

B type B aircraft

C type C aircraft

F final

I initial

i leading aircraft in a pair

j following aircraft in a pair

L lower approach path

min minimum value

U upper approach path

ANALYSIS METHOD

As used in this report, the landing capacity λ is defined as the number of landing operations that a single runway can accommodate during an hour when there is a continuous demand to land and each available landing opportunity is filled. It was also assumed that each arrival at the ILS gate was on time, and that no landing was constrained by the presence of the preceding aircraft on the runway. Although these assumptions are not suitable for reliable predictive modeling, the method chosen for the analysis provided a convenient, common basis

for comparing and evaluating the various methods. References 6 to 9 contain discussions of predictive methods more suitable for analysis of the broader aspects of air traffic control.

This study considered landing operations of commercial transport aircraft and no general aviation aircraft were included. Three types of commercial transports were considered in this study. Type A and B aircraft were those classified by air traffic control as "large" (ref. 10) and had take-off weights between 5670 and 136 078 kg (12 500 and 300 000 lbm). The type C aircraft were those classified in reference 10 as "heavy" and had take-off weights greater than 136 078 kg (300 000 lbm). The difference between the type A and B aircraft in this study was in the approach velocity V_A = 130 knots and V_B = 135 knots. For all type C aircraft, V_C = 140 knots.

Passenger capacity values ξ estimated by using a passenger load factor of 65 percent were $\xi_A = 85$, $\xi_B = 130$, and $\xi_C = 293$ passengers.

The landing capacity analyses for the current ILS method, the uniform speed method, and the reduced common path method were all performed by using the procedure of reference 6. The approach geometry for the analysis is shown in figure 1(a). The interarrival times for each aircraft pair were determined from the equations

$$t_{ij} = \frac{\delta_{ij}}{V_j} \qquad (V_i \leq V_j) \qquad (1)$$

$$t_{ij} = \frac{\delta_{ij}}{V_j} + \gamma\left(\frac{1}{V_j} - \frac{1}{V_i}\right) \qquad (V_i > V_j) \qquad (2)$$

where γ is the length of the approach path. Note in figure 1(a) that when $V_i \leq V_j$, the distance δ_{ij} occurred at the runway (solid aircraft symbols) and when $V_i > V_j$, the distance δ_{ij} occurred at the ILS gate (open aircraft symbols).

If it is assumed that the landing sequence was random, the probabilities of each pair sequence i-j were given by

$$p_{ij} = P_i P_j \qquad (3)$$

where P_i and P_j were the proportions of the types of i and j aircraft in the mix.

Table I presents the values of P_A, P_B, and P_C corresponding to the six mixes of aircraft used in this study. These mixes were derived from data in routine landing operation logs for the Kennedy International Airport in 1974 and 1975 (ref. 11, appendix B). It has been established, however, that reasonable changes in the proportions P_A and P_B did not significantly affect the calculated landing capacity values presented herein. (When the mixes were biased by simultaneously reducing each value of P_A by 0.1 and increasing P_B by the same amount, the maximum change in the landing capacity was about 1.4 percent.)

After t_{ij} and p_{ij} were determined for all possible pairs, the mean interarrival time $\bar{t}$ at the threshold was computed as

$$\bar{t} = \Sigma(t_{ij}p_{ij}) \tag{4}$$

(where the sum is over all possible pairs), and the landing capacity in operations/hr λ was determined by the equation

$$\lambda = \frac{1}{\bar{t}} 3600 \tag{5}$$

This method is suitable for all cases where the t_{ij} values between all pairs were unaffected by aircraft preceding the pairs.

The geometry of the curved-path method shown in figure 1(b) indicates that for a curved approach in the plane defined by θ, there is no specific value for the common flight path length γ as in single path approaches from the ILS gate. (See fig. 1(a).) This subject is discussed in detail in reference 6 which presents a general method of analysis for this approach concept. However, in the present analysis of curved paths, it was assumed that when every leading aircraft i had reached the runway, every following aircraft j was a distance δ_{ij} behind it on the common flight path. With this assumption, the fast-slow pairs were eliminated and the value of t_{ij} for curved paths was determined from equation (1) for all pairs.

The delayed flap method using a single approach path (fig. 1(a)) was analyzed with the single-path method modified to handle variable approach velocities. This procedure involved the determination of t_{ij} by a different technique described in the appendix. A similar method for variable velocity analysis is described in reference 12.

The geometric characteristics of the dual-path method using a single runway are shown in figures 1(c) to 1(e). This concept utilized two approach paths in the same vertical plane (defined by θ_L and γ_L and by θ_U and γ_U) with the projected touchdown points longitudinally offset by a distance x'. This geometry made it possible for the aircraft on the upper path to avoid the vortices of the aircraft on the lower path both during approach and at the runway surface.

The current separation intervals (see table II) were applied when aircraft i was on the upper path and aircraft j was on the lower path as shown in figure 1(c). The interarrival times were determined by

$$t_{ij} = \frac{\delta_{ij} - x'}{V_j \cos \theta_L} \qquad (V_i \cos \theta_U \leq V_j \cos \theta_L) \tag{6}$$

and by

$$t_{ij} = \frac{\delta_{ij} + \gamma_L \cos \theta_L}{V_j \cos \theta_L} - \frac{\gamma_U}{V_i} \qquad (V_i \cos \theta_U > V_j \cos \theta_L) \tag{7}$$

However, when i was on the lower path and j was on the upper path, the horizontal separation intervals were replaced with vertical separation intervals as shown in figures 1(d) and 1(e).

Figure 1(d) shows the geometric characteristics for i on the lower path and $V_i \sin \theta_L \leqq V_j \sin \theta_U$. The minimum vertical separation h_{min} occurs at the touchdown of aircraft i and produces a horizontal separation of

$$\delta_{ij,min} = \frac{h_{min}}{\tan \theta_U} - x' \tag{8}$$

The corresponding interarrival time is given by

$$t_{ij} = \frac{h_{min}}{V_j \sin \theta_U} \tag{9}$$

In this analysis h_{min} always had a value of 304.8 m (1000 ft) since lower values made runway occupancy time critical at $\theta_U = 6^o$. This value was also assumed to provide adequate vertical separation during all approaches using the dual-path method.

Figure 1(e) shows the geometry when i is on the lower path, j on the upper path, and $V_i \sin \theta_L > V_j \sin \theta_U$. For these conditions h_{min} occurred at the ILS gate. When aircraft i is at the touchdown point, the aircraft are vertically separated by a distance h where

$$h = (h_{min} + \gamma_L \sin \theta_L) - \frac{\gamma_L}{V_i} V_j \sin \theta_U \tag{10}$$

and horizontally separated by a distance Δ where

$$\Delta = \frac{h}{\tan \theta_U} - x' \tag{11}$$

The resulting interarrival time is determined from the equation

$$t_{ij} = \frac{h}{V_j \sin \theta_U} \tag{12}$$

Table III shows a typical analysis to illustrate this concept where $\theta_L = 3^o$, $\theta_U = 4.5^o$, $x' = 243.8$ m (800 ft), and $\gamma_L = 14.82$ km (8 n. mi.). The proportions in the mix were $P_A = 0.2$, $P_B = 0.2$, and $P_C = 0.6$. Note that in this case when i is on the lower path and j is on the upper path the condition $V_i \sin \theta_L > V_j \sin \theta_U$ is always satisfied.

The possible pairs are listed in column 1 of table III. These data show that landings always alternated between the two paths (no consecutive landings from the same path) and that all aircraft types were free to use either path. The δ_{ij} values in column 2 show that the current (horizontal) separation intervals from table II were applied whenever aircraft i was on the upper path and aircraft j was on the lower path. When the pair sequence was reversed, $\delta_{ij,min}$, determined from equation (8), was used as shown in column 3. The rest

of the analysis was straightforward - equations (6), (9), and (12) being used to solve for t_{ij}; equation (3), to solve for p_{ij}; and equations (4) and (5), to solve for $\bar{t}$ and λ, respectively. Since this method involved two approach paths, the values of p_{ij} in column (9) were the values determined from equation (3) divided by two.

As the analysis of the dual-path method progressed, it was found that if $\theta_U = 6^o$, the condition of the analysis which required that each aircraft pair be independent of the aircraft preceding the pair could not in some cases be maintained with the current separation intervals. This loss of independence existed whenever a C_U-A_L or C_U-B_L pair occurred and the required value of δ_{ij} (tables II and III) was greater than 8.14 km (4.4 n. mi.). Therefore in the analysis of the dual-path method where $\theta_U = 6^o$, the value of δ_{ij} for the C_U-A_L and C_U-B_L pairs was taken as 8.14 km (4.4 n. mi.) rather than 9.25 km (5 n. mi.). It has been determined that the effect on the landing capacity of using δ_{ij} = 8.14 km (4.4 n. mi.) rather than 9.25 km (5 n. mi.) was negligible for these two pairs when $\theta_U = 6^o$. This adjustment was not required for this method when reduced longitudinal separation intervals were studied.

In the dual-path-curved method, each aircraft j was always a distance δ_{ij} or $\delta_{ij,min}$ behind aircraft i when aircraft i was at the touchdown point. Therefore, when i landed from the upper path, t_{ij} was always determined from equation (6) and when i landed from the lower path, t_{ij} was always calculated from equation (9). When standard separation intervals were being studied and $\theta_U = 6^o$, the value of δ_{ij} between the C_U-A_L and C_U-B_L pairs was taken as 8.14 km (4.4 n. mi.) rather than 9.25 km (5 n. mi.) as described for the dual-path analysis.

After values of λ were determined, it was possible to calculate the corresponding values of the passenger delivery capacity μ for all seven methods by the equation

$$\mu = \lambda\left[P_A\xi_A + P_B\xi_B + P_C\xi_C\right] \tag{13}$$

It can be noted from equation (13) that μ is directly proportional to λ for a given mix of aircraft.

RESULTS AND DISCUSSION

The results of the analysis of seven approach methods are discussed in this section of the paper. The methods are

(1) Current ILS method

(2) Uniform speed method

(3) Reduced common path length method

(4) Curved-path method

(5) Delayed flap method

(6) Dual-path method

(7) Dual-path-curved method

The results are presented first for the current separation intervals and then for reduced separation intervals. The final part of this section presents a summary evaluation of the landing capacity data and also shows the effect of aircraft size on the passenger delivery capacity.

Current Separation Intervals

Current ILS method (baseline).- The current approach method using the ILS guidance system is illustrated in figure 2. Each aircraft begins its approach at the ILS gate and descends at constant approach speed along the glide slope by using guidance information from the ILS system. This information includes vertical and lateral glide slope deviations and discrete signals which indicate passage of the outer, middle, and inner stationary markers. Since all aircraft use a common path, minimum longitudinal IFR separation intervals are imposed.

The conditions for the baseline analysis (using current separation intervals) are

$\theta = 3^\circ$

Random arrival sequence

$\gamma = 14.82$ km (8 n. mi.)

$V_A = 130$ knots

$V_B = 135$ knots

$V_C = 140$ knots

The current longitudinal separation intervals δ_{ij} are listed in table II and were the values specified in reference 10. The values of $\delta_{ij} = 5.56$ km (3 n. mi.) are current IFR separation standards and the values of 7.40 km (4 n. mi.) and 9.25 km (5 n. mi.) are current wake turbulence avoidance intervals behind jets classified as "heavy."

The results of the landing capacity λ analysis are given in figure 3. The proportion of type C aircraft in current mixes at major U.S. airports (ref. 3) is also shown. Since $P_C = 0.2$ (20 percent type C aircraft in the mix) was near the center of the band, this value was used for comparing landing capacity results for a current mix.

Figure 3 illustrates that the baseline landing capacity initially decreased as the percentage of type C aircraft increased. When the mix contained more than about 70 percent type C aircraft, the landing capacity remained essentially constant. This same trend is shown in references 3 and 13. The trend results from the relations shown in equations (1) and (2); these equations show that the

interarrival time t_{ij} between any aircraft pair is increased when the separation interval δ_{ij} is increased or when $V_i > V_j$. Table IV presents the interarrival times for this baseline case. For the cases when the leading aircraft was a type C aircraft, both of these effects occurred and the interarrival time was significantly increased.

Uniform speed method.- A uniform speed method was discussed in reference 14 as a means of increasing landing capacity by eliminating the adverse effects of fast-slow pairs. In this analysis, all conditions were the same as for the baseline case except that all the aircraft types had an approach speed of 140 knots.

The results are shown in figure 4 and compared with the baseline method described in the previous section. These data show that the landing capacity was only about 5 to 6 percent greater than the baseline values when the proportion of type C aircraft was low and the landing capacity approached the baseline values as this proportion increased. This decrease occurred because of the reduced velocity differences by the higher proportions of type C aircraft. It should be noted, however, that although the landing capacity was not significantly affected by approach speed for the conditions of this study, unpublished Langley Research Center data obtained by S. K. Park and T. A. Straeter show that this effect is significant when velocity differences are large.

Reduced common path length method.- Another means of reducing the adverse effect on landing capacity of the fast-slow pairs shown in table IV is to reduce the length of the common approach path γ. An analysis was performed by using the same inputs as the baseline case except that values of γ = 18.52 km (10 n. mi.) and γ = 9.25 km (5 n. mi.) were used for the common path length.

It was found that for the approach speeds and mixes used in this study, this effect was also very small as indicated by the following table:

γ		λ, operations/hr at -					
km	n. mi.	$P_C = 0$	$P_C = 0.2$	$P_C = 0.4$	$P_C = 0.6$	$P_C = 0.8$	$P_C = 1.0$
9.25	5	43.7	39.2	36.5	34.9	34.5	35.0
18.52	10	43.1	38.4	35.8	34.2	34.1	35.0

This result is consistent with the conclusion in reference 6 for the case where velocity differences are small. However, that reference also shows that the common path length can be a significant factor when velocity differences are large.

Curved-path method.- The curved-path method will utilize the MLS guidance system described in references 1 and 2 to provide variable approach courses and glide slopes to the runway. Curved approaches will provide a number of advantages such as reduced airport traffic conflicts and delays, shorter arrival

route lengths, and reduced noise impact (ref. 3). Since this method may provide reduced common path lengths, an increase in the landing capacity is also possible.

The curved-path method analyzed in this study is shown in figure 5. All the conditions were the same as those for the baseline case except that for all pairs t_{ij} was the time required for aircraft j to traverse the distance δ_{ij}.

The results in figure 6 show that for the conditions of this study, the effect of the curved-path method was small. This result is the same as that of the uniform speed and reduced common path length methods. In the three cases, the results showed that for the typical commercial jet aircraft types used in this study, incremental speed differences did not have a significant influence on landing capacity.

Delayed flap method.- Delayed flap approaches are currently receiving considerable attention since they offer the potential advantages of lower approach noise and reduced fuel consumption. This method is initiated with high approach speed, low thrust, and low drag. At appropriate times after the aircraft passes the ILS gate, the landing gear and flaps are lowered so that the aircraft decelerates to the normal approach velocity at an altitude of approximately 183 m (600 ft). The technique can be used with single flight paths, multiple flight paths, or segmented paths. Some recent studies and experiments with delayed flap approaches are described in references 15 to 18.

Figure 7 illustrates the two deceleration schedules used in the study in terms of speeds as a function of distance from the projected touchdown point. Schedule 1 was used by all type A aircraft and schedule 2 was used by all type B and C aircraft. It can be noted that schedule 2 was generally the faster of the two schedules and that both schedules show velocities higher than the baseline values beyond about $x = 3$ km (1.6 n. mi.). These schedules were believed to be feasible and sufficiently representative for use in this study.

In this analysis the landing capacity was determined for three conditions: (1) only the type A aircraft in the mix used the delayed flap method, (2) only type A and B aircraft used this method, and (3) all aircraft in the mix used this method. It should be noted that the delayed flap method required $\gamma = 18.52$ km (10 n. mi.). Therefore, the data are compared in figure 8 with baseline values using $\gamma = 18.52$ km (10 n. mi.) rather than with the previously used baseline values where $\gamma = 14.82$ km (8 n. mi.). The differences between these baseline results, however, were found to be sufficiently small (always less than 1 percent) to justify comparison with the previously used baseline values.

The data in figure 8 show that when only the type A aircraft in the mix used this method, there was a slight loss in landing capacity at mixes with less than about 30 percent type C aircraft, and when both types A and B used this method, there was a slight increase in the landing capacity in this range. When all the aircraft in the mix used this method, the landing capacity was greater than that for the current method for all the mixes. For a mix containing 20 percent type C aircraft, the increase was about 13 percent.

These results can be explained with the interarrival time data presented in table V. These data indicate that the reduction in landing capacity, noted when only the type A aircraft used this method and the proportion of type C aircraft was small, was an adverse velocity effect that resulted in increases in t_{ij} for the fast-slow aircraft pairs A-B and A-C. When both type A and B aircraft used this method, the velocity effect was favorable in this region and the gains resulted from reductions in t_{ij} for all the possible type A and B aircraft combinations. When all the aircraft used this method, the velocity effect resulted in reduced values of t_{ij} for all possible pairs.

Dual-path method.- With MLS guidance it will also be feasible to make dual-path approaches. The study reported in reference 6 introduced the concept of longitudinal and vertical separation between aircraft on dual paths and concluded that significant increases in landing capacity could be achieved with this concept.

Figure 9 illustrates the three dual-path configurations analyzed in the present study. Since the vortices from the aircraft on the lower path do not present a hazard to the aircraft on the upper paths, it was possible to use reduced longitudinal intervals $\delta_{ij,min}$ when aircraft i was on the lower path and aircraft j was on an upper path. (See figs. 1(d) and 1(e).) For the three path configurations shown in figure 9, the $\delta_{ij,min}$ values (from eq. (8)) were 5.57, 3.63, and 2.65 km (3.01, 1.96, and 1.43 n. mi.) for the values of $\theta_U = 3^\circ$, 4.5°, and 6°, respectively. As noted earlier, for the configuration where $\theta_U = 6^\circ$, it was necessary to use $\delta_{ij} = 8.14$ km (4.4 n. mi.) rather than $\delta_{ij} = 9.25$ km (5 n. mi.) for the longitudinal interval between the C_U-A_L and C_U-B_L pairs.

Three strategies for utilizing the dual-path geometry were investigated. In each strategy both paths were utilized equally, but the probability terms p_{ij} were manipulated to investigate the following:

(1) Alternating landing strategy: This is the strategy described earlier and illustrated in table III. All aircraft types were free to use either path, and landings always alternated between aircraft on each path.

(2) Preferred path strategy: This strategy was that when $P_C < 0.5$, all type C aircraft were restricted to the lower path and all the type A and B aircraft could use either path. When $P_C > 0.5$, the type A and B aircraft were restricted to the upper path and the type C aircraft used both paths. Alternate landings between the paths were not required.

(3) Free option strategy: This strategy allowed all aircraft types to use either path but did not require alternate landings between the paths.

This investigation showed that the landing capacities for the preferred path and free option strategies had essentially the same values and were 5 to 8 operations/hr less than the alternating landing strategy for all the aircraft mixes. The lower landing capacity for the preferred path and free option strategies occurred because there was less opportunity to take advantage of the benefits afforded by $\delta_{ij,min}$ over δ_{ij}. For this reason the landing capacity results presented for the dual-path and dual-path-curved methods were determined

for the alternating landing strategy. It should be noted, however, that the other two strategies (particularly the free option strategy) may offer operational advantages which could compensate for their slightly reduced effectiveness.

The results of the dual-path method are compared with the baseline data in figure 10 and show gains for all three path configurations. The landing capacity values were larger for the configurations with steeper upper slopes. For a mix of 20 percent type C aircraft, this method increased the landing capacity by 24 percent for $\theta_U = 4.5^\circ$ and 39 percent for $\theta_U = 6^\circ$. These gains were larger than those for any of the preceding methods using the current longitudinal separation intervals. However, as with the other methods using these intervals, the landing capacity values decreased as the proportion of type C aircraft increased.

It should be noted that with the dual-path method, the more shallow upper path configurations ($\theta_U = 3^\circ$ and $\theta_U = 4.5^\circ$) could provide essentially the same landing capacity as the $\theta_U = 6^\circ$ configuration if the minimum vertical separation distance h_{min} was reduced to achieve the same value of $\delta_{ij,min}$. (For $\theta_U = 3^\circ$, the required value of h_{min} would be 152.4 m (500 ft).) Additional studies are needed to determine optimum combinations of approach path angles and vertical separation requirements. For example, the steeper approach paths with large vertical separations may be more difficult to negotiate for some classes of aircraft. On the other hand, the more shallow approach paths with reduced vertical separations may be impractical because of air traffic control limitations.

Dual-path-curved method.- The dual-path-curved method is illustrated in the sketch shown in figure 11. With this method, aircraft use MLS position and guidance information to make curved approaches in both the lower plane θ_L and the upper plane θ_U. In the analysis, it was assumed that when aircraft i had landed, aircraft j was a distance δ_{ij} or $\delta_{ij,min}$ behind it. As previously noted, when $\theta_U = 6^\circ$, it was necessary to use $\delta_{ij} = 8.14$ km (4.4 n. mi.) rather than $\delta_{ij} = 9.25$ km (5 n. mi.) for the C_U-A_L and C_U-B_L pairs.

The results shown in figure 12 indicate that the trends are similar to those for the dual-path method in figure 10. Each path configuration showed a gain over the baseline and the gains increased, at a given mix, as the angle of the upper path increased. These gains resulted from the reduced values of $\delta_{ij,min}$ which were obtained at the larger values of θ_U (eq. (6)). A comparison of the data in figure 12 with the data in figure 10 indicates that the gains resulting from curved paths were not large, which is consistent with the results of the curved path (single plane) analysis presented in the section "Curved-Path Method."

Of all the methods using current longitudinal separation intervals, the dual-path-curved method provided the largest increases in landing capacity (28 percent and 46 percent for $\theta_U = 4.5^\circ$ and $\theta_U = 6^\circ$, respectively) at a typical mix containing 20 percent type C aircraft. As with all the other methods using current longitudinal separation intervals, the landing capacity decreased as the proportion of type C aircraft in the mix increased.

Reduced Separation Intervals

Reduced separation intervals have received a great deal of attention by both NASA and the DOT and indications are that some reductions in the current separation intervals may become possible. Data in reference 4, for example, indicate that the vortex hazard near the threshold is strongly influenced by surface wind conditions, and that under some wind conditions, the wake turbulence separation interval might be reduced to 5.56 km (3 n. mi.) between all aircraft. Reference 3 indicates that within the next 10 years, a reduction to 3.70 km (2 n. mi.) with variable spacing for wake turbulence can be expected, and data in reference 5 indicate that the development of aerodynamic means of attenuating flight vortices appears to be promising.

An analysis was performed to evaluate the effect of reduced separation intervals. A reduced separation interval of 5.56 km (3 n. mi.) was selected for all pairs on the basis of the discussion in reference 4, as well as a second interval of 3.70 km (2 n. mi.) for all pairs. This latter interval is beyond the state of the art at this time (ref. 3) but was chosen as a goal which might eventually be reached as a result of continued vortex attenuation research and advanced air traffic control system developments.

Figure 13 shows the landing capacity for the current method using these reduced intervals. These results are compared with the baseline data and show that the increase obtained by reducing the current intervals to 5.56 km (3 n. mi.) was not particularly large in the current range of typical mixes (10 percent to 40 percent type C aircraft). Reducing the current intervals to 3.70 km (2 n. mi.), however, increased the landing capacity significantly (65 percent) at a mix of 20 percent type C aircraft, and clearly emphasizes the benefits associated with large reductions in the current separation intervals. It is also interesting to note that with either of the reduced intervals, the landing capacity values increased with an increasing proportion of type C aircraft rather than decreased as with all the methods using the current intervals. This same trend is shown by the data in reference 3 and results from the large reductions in δ_{ij} behind the type C aircraft.

Values of λ for the reduced common path length method with reduced separation intervals were essentially the same as those for the current method with reduced intervals (fig. 13) and are not presented in a separate figure.

At either of the reduced δ_{ij} values, the landing capacity values for the uniform speed method (fig. 14), the curved-path method (fig. 15), and the delayed flap method (fig. 16) did not differ significantly from the values for the current method with reduced separation intervals shown in figure 13. This result is consistent with data shown for these methods previously when the current separation intervals were used and indicates that these particular methods do not provide significant increases over the current method regardless of the separation intervals used.

The gains in landing capacity offered by all these methods with reduced separation intervals were large when compared with the baseline data, particularly when $\delta_{ij} < 5.56$ km (3 n. mi.). It can also be noted that each of these

methods showed the same favorable increase in landing capacity with an increasing proportion of type C aircraft as shown in figure 13.

Figures 17 and 18 show the landing capacity at reduced separation intervals for the dual-path and the dual-path-curved methods, respectively. The landing capacity values shown for these methods were the largest found in this study and were approximately double those for the current method with current separation intervals. These gains were made possible by vortex avoidance advantage of the dual-path geometry in combination with a large reduction in spacing between pairs on the same path.

Another characteristic which makes these dual-path methods attractive is reduced noise. Data in reference 19 indicate that with steep approach paths, lower thrust settings are required and center-line noise is reduced. The increased path angle also provides a noise reduction by increasing the distance between an observer on the ground and the noise source.

Data Evaluation

The landing capacity results are summarized in figure 19 for a landing mix containing 20 percent type C aircraft. The results of the analysis of the reduced common path length method are not shown since they were essentially the same as were obtained with the current method. Figure 19 also shows a value of landing capacity limited only by the time required for aircraft i to clear the runway so that aircraft j can land. References 1 and 2 indicate that with properly designed runways, 40 to 45 seconds is a reasonable interval between arrivals; therefore, an interval of 40 seconds was used to determine the goal of 90 operations/hr shown in the figure.

The data in figure 19 show that with current separation intervals, the dual-path and dual-path-curved methods provided the largest gains over the current method. However, even these rates (≈54 operations/hr for the dual-path method and 56 operations/hr for the dual-path-curved method) were far below the 90 operations/hr goal. In addition, as noted earlier, the landing capacity values decreased for all the methods as the proportion of type C aircraft increased.

For all the methods considered, reducing the current longitudinal separation intervals to 5.56 km (3 n. mi.) increased the landing capacity by only about 6 operations/hr for this mix. A further reduction to 3.70 km (2 n. mi.), however, produced a very significant increase in landing capacity for every method. This large reduction in spacing, combined with the vortex avoidance advantages of the dual-path and dual-path-curved geometry, approximately doubled the landing capacity for the aircraft mix containing 20 percent type C aircraft. The gain in landing capacity achieved by using the dual-path-curved method, while maintaining the current longitudinal separation intervals, is shown to be equivalent to reducing the separation intervals to 3.70 km (2 n. mi.) with the current method. At higher proportions of type C aircraft, the gains were larger since the effect of the reduced separation intervals was particularly significant at these conditions. Figures 17 and 18, for example, show that when the proportion of type C aircraft was ≥80 percent, the landing capacity was approximately 80 operations/hr with these two methods.

Reference 3 notes that landing capacity is affected by the precision of the arrival time of the aircraft at the ILS gate. This effect was shown to be particularly significant at high landing capacities and reduced separation intervals. Since the arrival error was assumed to be zero throughout this analysis, the higher values shown in figures 17, 18, and 19 should be regarded as indicating trends rather than as values which might be expected in a current operational environment.

This study also included an analysis of the impact of these various methods and of aircraft size (passenger capacity) on the passenger delivery capacity μ as defined in equation (13). Some typical results are summarized as a function of the proportion of type C aircraft in the mix in figure 20. This figure also includes μ values for the 40-second landing interval discussed earlier. The data in figure 20 have all been normalized to the value of μ for the baseline conditions (5770 passengers/hr) at a mix of 20 percent type C aircraft.

The results show that for all the methods considered, the passenger delivery capacity always increased as the proportion of type C aircraft in the mix increased. This was true even for those methods which showed a decrease in the landing capacity with an increase in the proportion of type C aircraft (that is, figs. 3, 4, 6, 8, 10, and 12). The data in figure 20 also show that increasing the proportion of type C aircraft, with their large passenger capacities, is an extremely effective method of increasing passenger delivery capacity. This result indicates that the requirement to meet the anticipated increased demand for air transportation will necessitate not only advanced landing approach methods and large reductions in separation intervals, but also an increased proportion of high passenger capacity aircraft.

CONCLUDING REMARKS

Results have been presented of analyses of the effects on landing capacity of seven landing approach methods and of reduced separation intervals. The results have been compared with current baseline values and with a value based on a 40-second interval between arrivals. The effects of these methods and of aircraft size on the passenger delivery rate have also been shown.

The results showed that with current separation intervals, the uniform speed approach method, the reduced common path length method, the curved-path method, and the delayed flap method provided small gains in landing capacity over the current ILS method for the conditions and assumptions of this study. The dual-path and dual-path-curved methods produced the largest gains (39 percent and 46 percent, respectively) at a typical landing mix containing 20 percent heavy aircraft. The data also showed that for every method considered with the current separation intervals, the landing capacity decreased as the proportion of heavy aircraft increased.

Reducing the current separation intervals to 5.56 km (3 n. mi.) between all aircraft pairs provided only a small gain in landing capacity in the current range of mixes for any of the methods studied. An additional reduction to 3.70 km (2 n. mi.), however, provided significant increases in landing capacity for every method. In addition, with either of the reduced separation intervals,

it was found that there was a desirable increase in landing capacity with an increase in the proportion of heavy aircraft.

The reduction of the landing intervals to 3.70 km (2 n. mi.), when combined with the vortex avoidance advantage of dual-path and dual-path-curved methods gave the largest gains found in the study and approximately doubled the landing capacity for a current landing mix containing 20 percent heavy aircraft. At a mix containing 80 percent heavy aircraft, the gain was even larger and landing capacity values of approximately 80 operations/hr were achieved. The gain in landing capacity achieved by using the dual-path-curved method, while maintaining the current longitudinal separation intervals, was equivalent to reducing the separation intervals to 3.70 km (2 n. mi.) with the current method.

The results also showed that, for every method considered, an increase in the proportion of heavy (large passenger capacity) aircraft in the mix was very effective in increasing the passenger delivery capacity. This result indicates that increased demand for air transportation will probably require not only advanced landing approach methods and large reductions in separation intervals, but an increased proportion of high passenger capacity aircraft as well.

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November 15, 1977

APPENDIX

ANALYTICAL PROCEDURES FOR DETERMINING INTERARRIVAL TIMES FOR THE DELAYED FLAP METHOD

With the delayed flap method there were large parts of the approach trajectory where V was not constant as shown in figure 7. Schedule 1 shows variations in V between $x \approx 15$ km (8 n. mi.) and $x \approx 3$ km (1.6 n. mi.) and schedule 2, between about 18 and 4 km ($\approx$10 and $\approx$2 n. mi.).

In order to determine values of t_{ij} for this analysis, each of these schedules was represented by a number of constant deceleration segments duplicating the data in figure 7 at key points. Table VI lists the initial and final conditions of the constant deceleration segments used in this analysis.

$V_i \leqq V_j$

Equation (1) showed that when $V_i \leq V_j$, t_{ij} was determined only by the time required for aircraft j to traverse the distance δ_{ij}. Since with this technique the distance δ_{ij} usually covered a number of segments where V was changing, it was necessary to determine t for each segment and determine t_{ij} from the summation

$$t_{ij} = \Sigma t \tag{A1}$$

over the number of segments required.

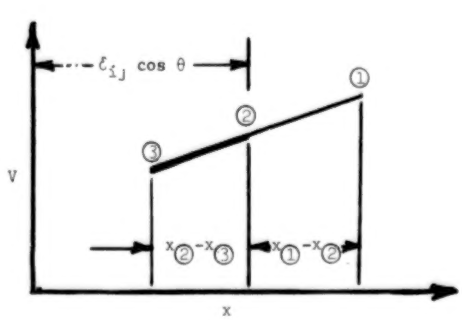
For each segment which was totally covered by δ_{ij}, t was given either by

$$t = \frac{2(x_I - x_F)}{(V_{j,I} + V_{j,F}) \cos \theta} \qquad (a \neq 0) \tag{A2}$$

or by

$$t = \frac{x_I - x_F}{V_j \cos \theta} \qquad (a = 0) \tag{A3}$$

In this analysis, the last segment was usually only partially covered by δ_{ij} and t was determined in a different manner. Consider the following sketch:



Assume that, of this segment, only the time required to traverse the path distance between points ② and ③ is required in the summation of equation (A1). In the case of this partial segment, the appropriate value of t was determined by

$$t = \frac{1}{a}\left(V_{j,F} - \sqrt{V_{j,F}^2 - 2a\,\frac{x_{②} - x_{③}}{\cos\theta}}\right) \tag{A4}$$

$V_i > V_j$

For fast-slow pairs, equation (2) was applicable when the values of V were constant. For the delayed flap method, however, the values of t_{ij} were given by

$$t_{ij} = t_{j,\mathrm{total}} - t_{i,\mathrm{total}} + \frac{\delta_{ij}}{V_j} \tag{A5}$$

In this equation $t_{j,\mathrm{total}}$ and $t_{i,\mathrm{total}}$ were the total times required for aircraft i and j to traverse all the segments listed in table VI for the appropriate schedule. For each of these segments, t was determined from either equation (A2) or (A3). The last term in equation (A5) was solved by using a constant value of V_j since, as shown in figure 1(a), δ_{ij} is beyond the ILS gate when $V_i > V_j$ and none of the aircraft initiate deceleration prior to reaching that point.

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TABLE I.- PROPORTIONS OF AIRCRAFT TYPES USED IN STUDY

	P_A	P_B	P_C
1	0.40	0.60	0
2	.30	.50	.20
3	.20	.40	.40
4	.20	.20	.60
5	.10	.10	.80
6	0	0	1.00

TABLE II.- SEPARATION INTERVALS USED IN STUDY

Aircraft pair		δ_{ij}		Remarks
i	j	km	n. mi.	
A	A	5.56	3	Current IFR longitudinal separation standards
A	B	5.56	3	
A	C	5.56	3	
B	A	5.56	3	
B	B	5.56	3	
B	C	5.56	3	
C	A	9.25	5	Current wake turbulence avoidance intervals
C	B	9.25	5	
C	C	7.40	4	

TABLE III.- TYPICAL ANALYSIS FOR DUAL-PATH METHOD

[Conditions:
θ_L = 3°
θ_U = 4.5°
h_{min} = 304.8 m (1000 ft)
x' = 243.8 m (800 ft)
γ_L = 14.82 km (8 n. mi.)
γ_U = 15.08 km (8.15 n. mi.)
P_A = 0.2
P_B = 0.2
P_C = 0.6]

① Aircraft pair i	① Aircraft pair j	② δ_{ij}, km (n. mi.)	③ $\delta_{ij,min}$, km (n. mi.)	④ V_i, knots	⑤ V_j, knots	⑥ γ_i, km	⑦ γ_j, km	⑧ t_{ij}, sec	⑨ p_{ij}	⑩ $t_{ij}p_{ij}$, sec
A_L	A_U	---- (----)	3.63 (1.96)	130	130	14.82	15.08	58.8	0.02	1.18
A_U	A_L	5.56 (3)	---- (----)	130	130	15.08	14.82	79.7	.02	1.59
A_L	B_U	---- (----)	3.63 (1.96)	130	135	14.82	15.08	56.7	.02	1.13
A_U	B_L	5.56 (3)	---- (----)	130	135	15.08	14.82	76.9	.02	1.54
A_L	C_U	---- (----)	3.63 (1.96)	130	140	14.82	15.08	54.8	.06	3.29
A_U	C_L	5.56 (3)	---- (----)	130	140	15.08	14.82	74.2	.06	4.45
B_L	A_U	---- (----)	3.63 (1.96)	135	130	14.82	15.08	58.8	.02	1.18
B_U	A_L	5.56 (3)	---- (----)	135	130	15.08	14.82	87.4	.02	1.75
B_L	B_U	---- (----)	3.63 (1.96)	135	135	14.82	15.08	56.7	.02	1.13
B_U	B_L	5.56 (3)	---- (----)	135	135	15.08	14.82	76.9	.02	1.54
B_L	C_U	---- (----)	3.63 (1.96)	135	140	14.82	15.08	54.8	.06	3.29
B_U	C_L	5.56 (3)	---- (----)	135	140	15.08	14.82	74.2	.06	4.45
C_L	A_U	---- (----)	3.63 (1.96)	140	130	14.82	15.08	58.8	.06	3.53
C_U	A_L	9.25 (5)	---- (----)	140	130	15.08	14.82	150.8	.06	9.05
C_L	B_U	---- (----)	3.63 (1.96)	140	135	14.82	15.08	56.7	.06	3.40
C_U	B_L	9.25 (5)	---- (----)	140	135	15.08	14.82	138.3	.06	8.30
C_L	C_U	---- (----)	3.63 (1.96)	140	140	14.82	15.08	54.8	.18	9.86
C_U	C_L	7.40 (4)	---- (----)	140	140	15.08	14.82	100.0	.18	18.00

$$\bar{t} = \Sigma(t_{ij}p_{ij}) = 78.56 \text{ sec}$$

$$\lambda = \frac{3600}{\bar{t}} = 45.82 \text{ operations/hr}$$

TABLE IV.- INTERARRIVAL TIMES FOR THE CURRENT ILS METHOD

(BASELINE) AND γ = 14.82 km (8 n. mi.)

Aircraft pair		δ_{ij}, km (n. mi.)	V, knots		t_{ij}, sec
i	j		i	j	
A	A	5.56 (3)	130	130	83.1
A	B	5.56 (3)	130	135	80.0
A	C	5.56 (3)	130	140	77.1
B	A	5.56 (3)	135	130	91.3
B	B	5.56 (3)	135	135	80.0
B	C	5.56 (3)	135	140	77.1
C	A	9.25 (5)	140	130	154.3
C	B	9.25 (5)	140	135	141.0
C	C	7.40 (4)	140	140	102.9

TABLE V.- INTERARRIVAL TIMES FOR DELAYED FLAP METHOD

Aircraft pair		δ_{ij}, km (n. mi.)	Current method with γ = 18.52 km			Delayed flap method								
						Type A only			Type A and B only			All aircraft		
			V, knots		t_{ij}, sec	V, knots		t_{ij}, sec	V, knots		t_{ij}, sec	V, knots		t_{ij}, sec
i	j		i	j		i	j		i	j		i	j	
A	A	5.56 (3)	130	130	83.1	①	①	80.9	①	①	80.9	①	①	80.9
A	B	5.56 (3)	130	135	80.0	①	135	131.0	①	②	73.9	①	②	73.9
A	C	5.56 (3)	130	140	77.1	①	140	118.6	①	140	118.6	①	②	73.9
B	A	5.56 (3)	135	130	92.7	135	①	80.9	②	①	82.4	②	①	82.4
B	B	5.56 (3)	135	135	80.0	135	135	80.0	②	②	73.9	②	②	73.9
B	C	5.56 (3)	135	140	77.1	135	140	77.1	②	140	150.5	②	②	73.9
C	A	9.25 (5)	140	130	157.8	140	①	126.0	140	①	126.0	②	①	116.0
C	B	9.25 (5)	140	135	143.4	140	135	142.8	140	②	108.7	②	②	108.7
C	C	7.40 (4)	140	140	102.9	140	140	102.9	140	140	102.9	②	②	92.3

① denotes schedule 1 (type A aircraft).
② denotes schedule 2 (type B and C aircraft).

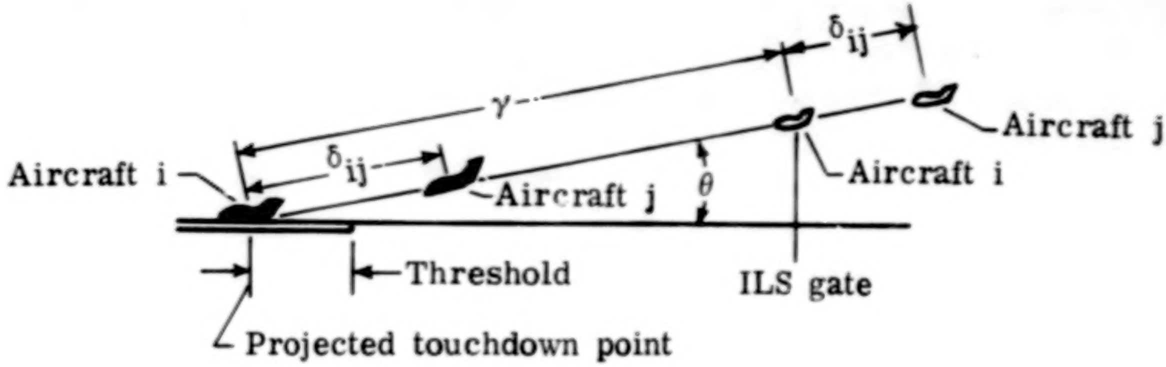
TABLE VI.- DECELERATION SCHEDULES USED IN DELAYED FLAP METHOD

(a) Schedule 1: type A aircraft

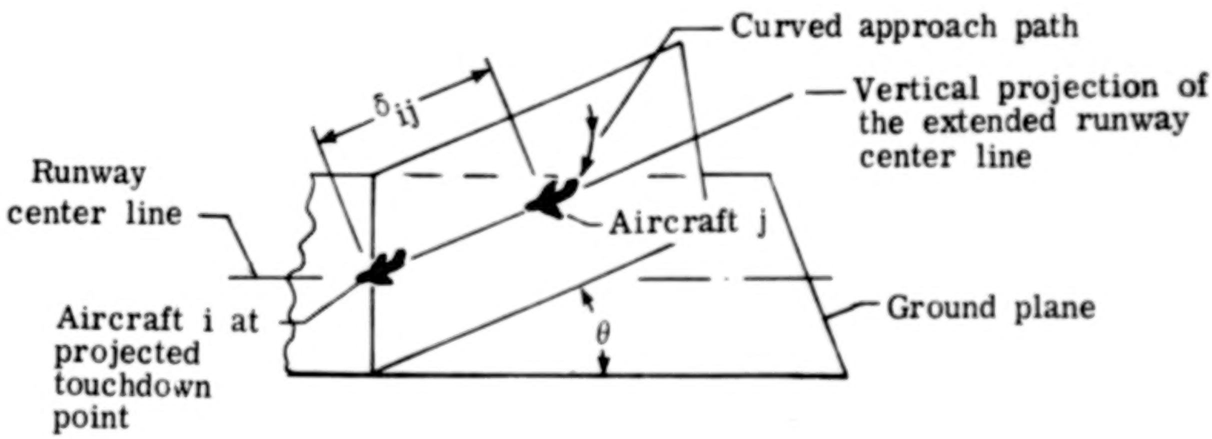
Segment	V, knots		h, m (ft)		x, m (ft)		a, m/sec^2 (ft/sec^2)
	Initial	Final	Initial	Final	Initial	Final	
1	214	214	969.3 (3180)	780.3 (2560)	18 520 (60 761)	14 909 (48 915)	0
2	214	170	780.3 (2560)	470.9 (1545)	14 909 (48 915)	8 998 (29 521)	-.38 (-1.24)
3	170	150	470.9 (1545)	307.9 (1010)	8 998 (29 521)	5 882 (19 298)	-.27 (-.89)
4	150	140	307.9 (1010)	244.5 (810)	5 882 (19 298)	4 717 (15 477)	-.33 (-1.08)
5	140	130	244.5 (810)	152.4 (500)	4 717 (15 477)	2 912 (9 554)	-.20 (-.65)
6	130	130	152.4 (500)	0	2 912 (9 554)	0	0

(b) Schedule 2: type B and C aircraft

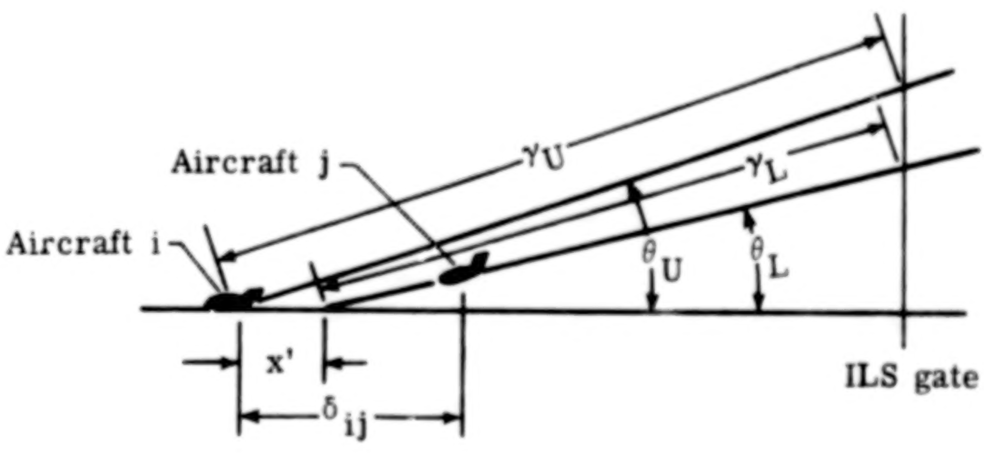
Segment	V, knots		h, m (ft)		x, m (ft)		a, m/sec^2 (ft/sec^2)
	Initial	Final	Initial	Final	Initial	Final	
1	250	231	971.1 (3186)	502.9 (1650)	18 532 (60 800)	9 596 (31 484)	-0.13 (-0.44)
2	231	219	502.9 (1650)	435.9 (1430)	9 596 (31 484)	8 617 (27 286)	-.56 (-1.83)
3	219	205	435.9 (1430)	365.8 (1200)	8 617 (27 286)	6 979 (22 897)	-.59 (-1.93)
4	205	140	365.8 (1200)	192.0 (630)	6 979 (22 897)	3 664 (12 021)	-.90 (-2.94)
5	140	140	192.0 (630)	0	3 664 (12 021)	0	0



(a) Single path. Solid aircraft symbols denote $V_i \leq V_j$; open aircraft symbols denote $V_i > V_j$.

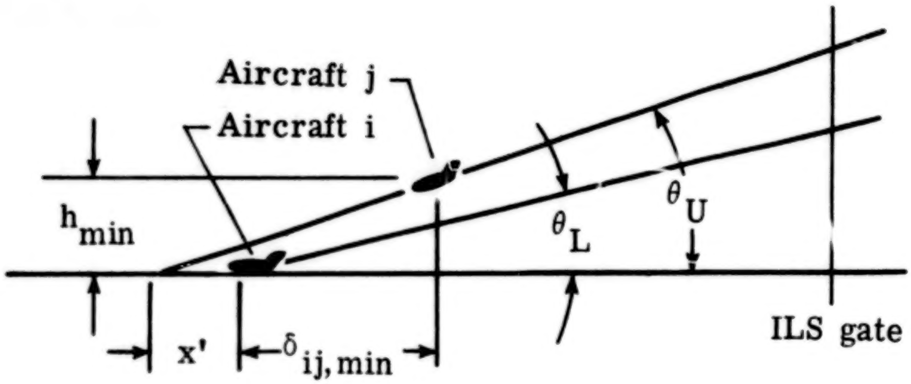


(b) Curved path.

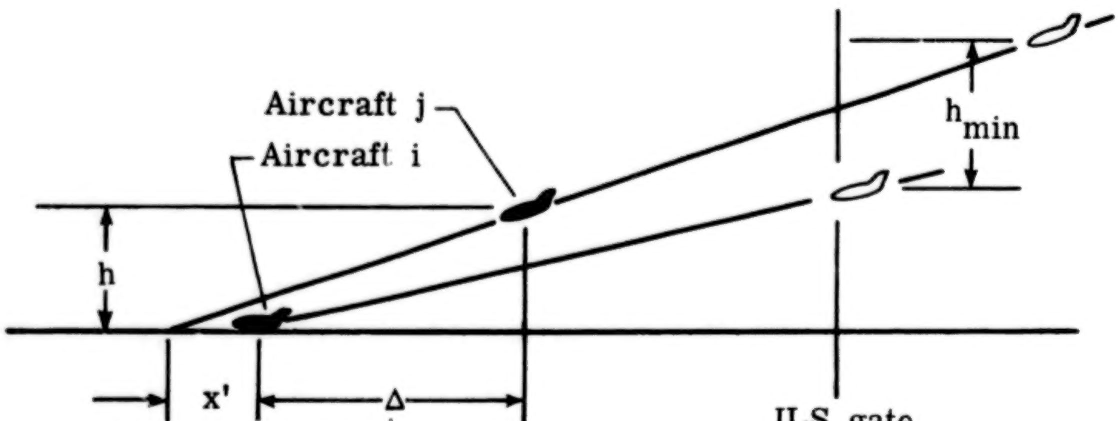


(c) Dual path: aircraft i on upper path; aircraft j on lower path.

Figure 1.- Geometric characteristics of approach paths.



(d) Dual path: aircraft i on lower path; aircraft j on upper path; $V_i \sin \theta_L \leqq V_j \sin \theta_U$.



(e) Dual path: aircraft i on lower path; aircraft j on upper path; $V_i \sin \theta_L > V_j \sin \theta_U$.

Figure 1.- Concluded.

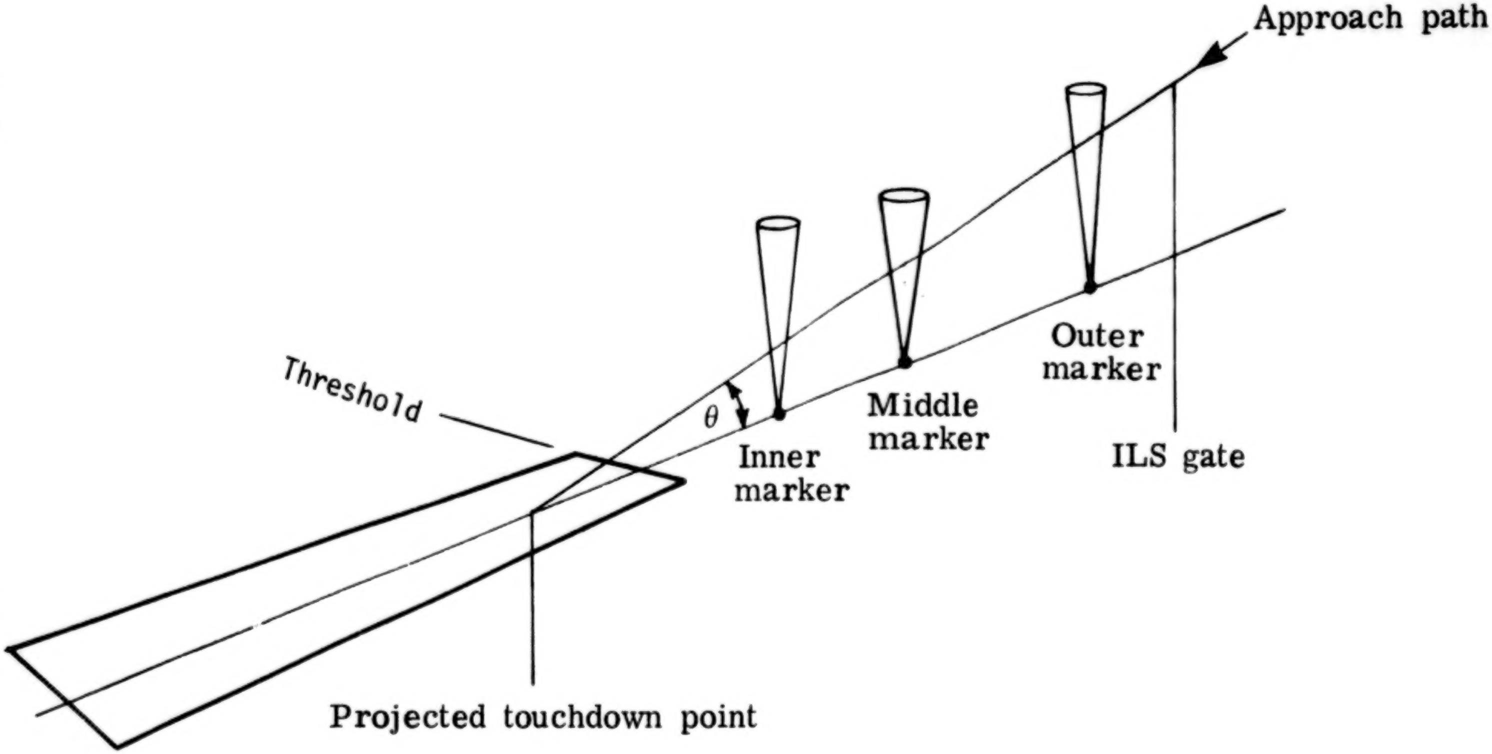


Figure 2.- Sketch illustrating current ILS method.

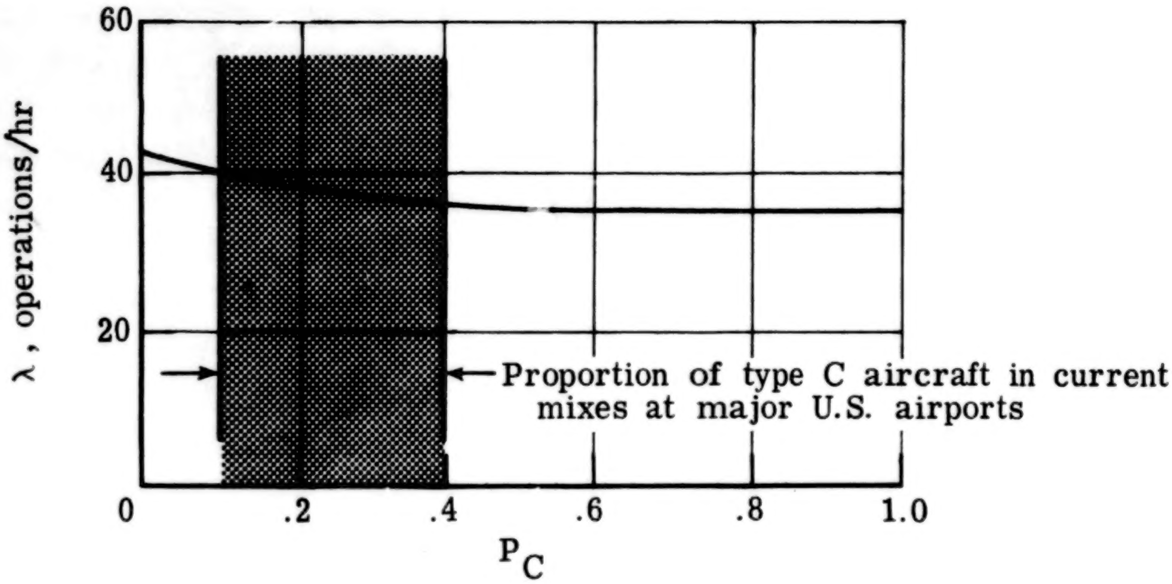


Figure 3.- Landing capacity for current ILS method and separation intervals.

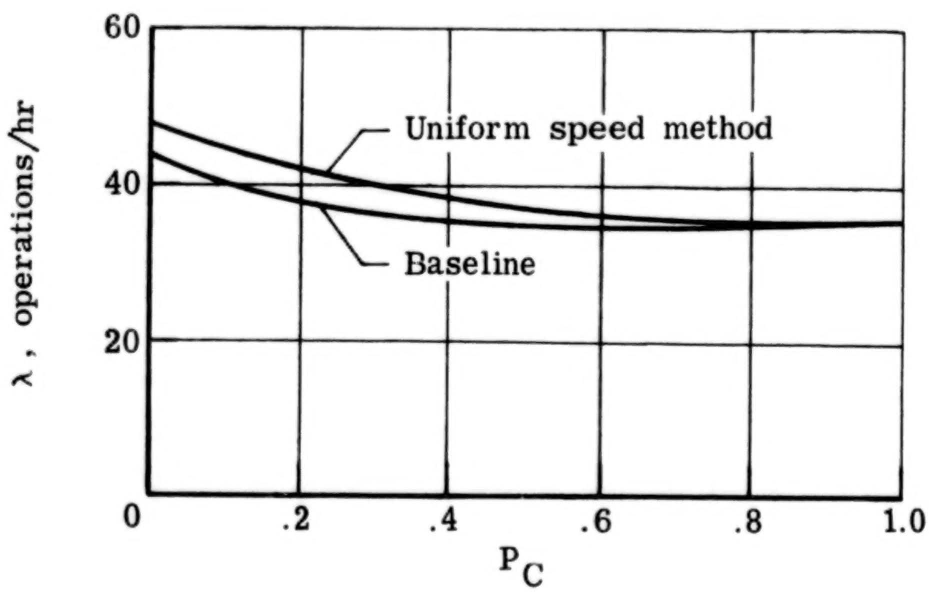


Figure 4.- Landing capacity for uniform speed method.

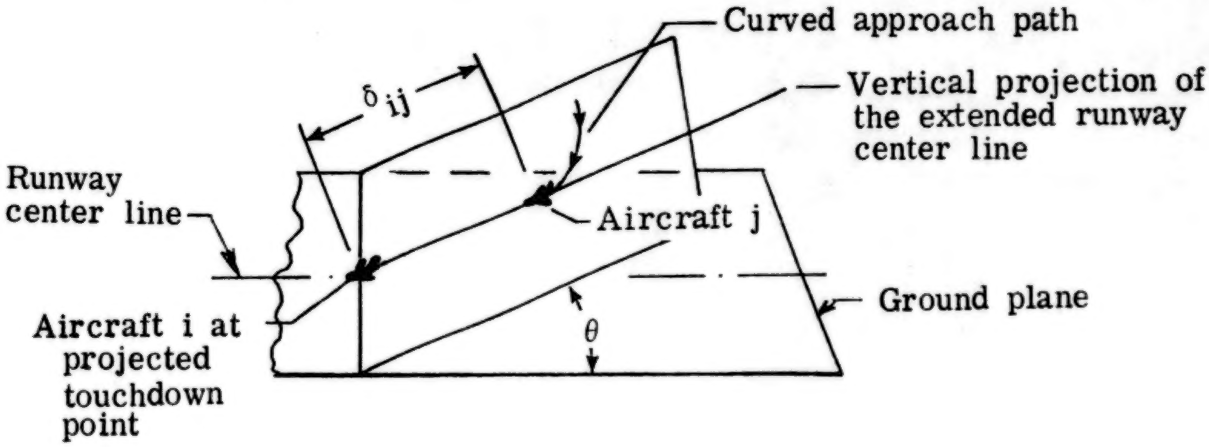


Figure 5.- Sketch illustrating curved-path method.

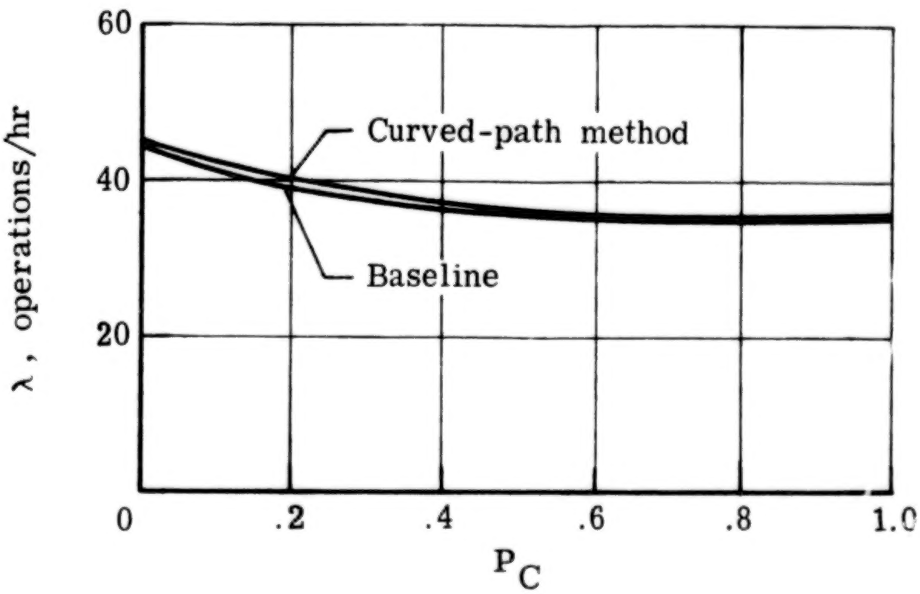


Figure 6.- Landing capacity for curved-path method.

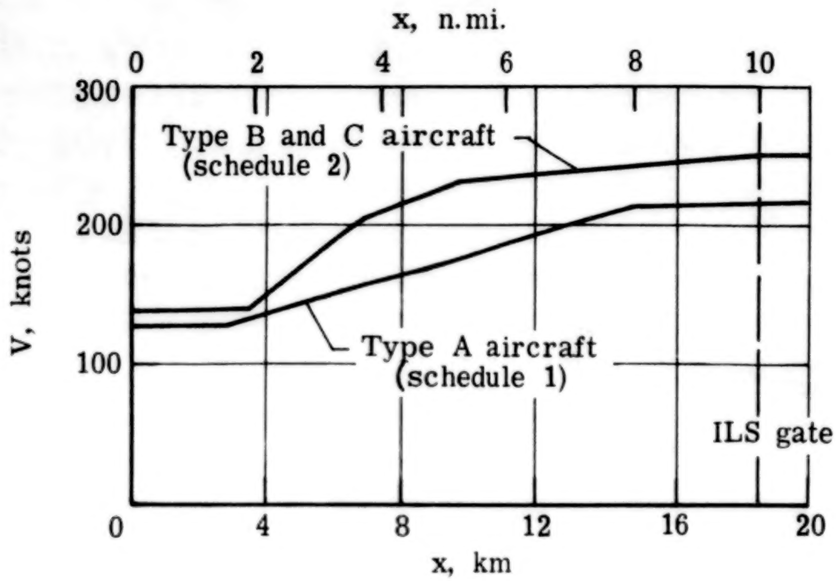


Figure 7.- Deceleration schedules used in analysis of delayed flap method.

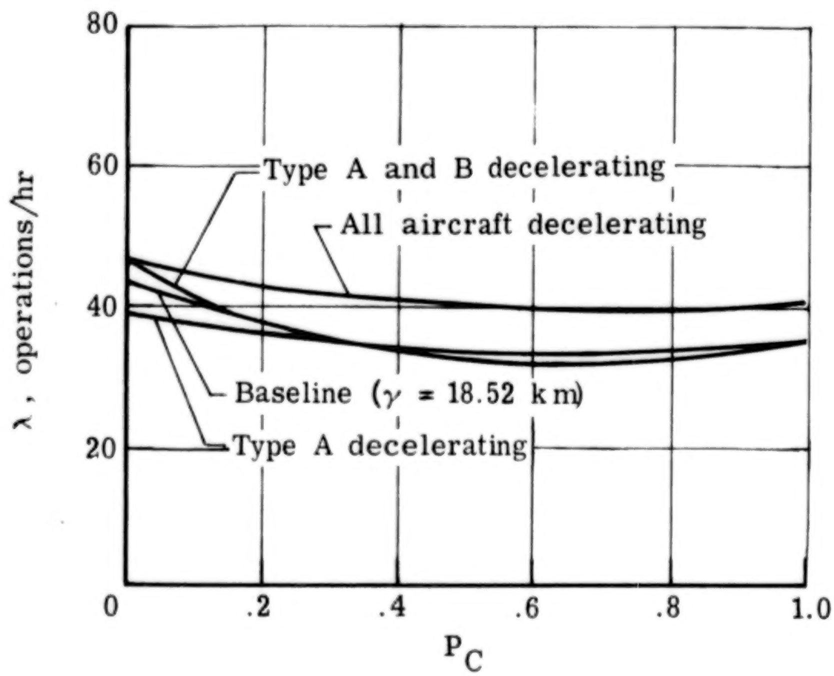


Figure 8.- Landing capacity for delayed flap method using current separation intervals.

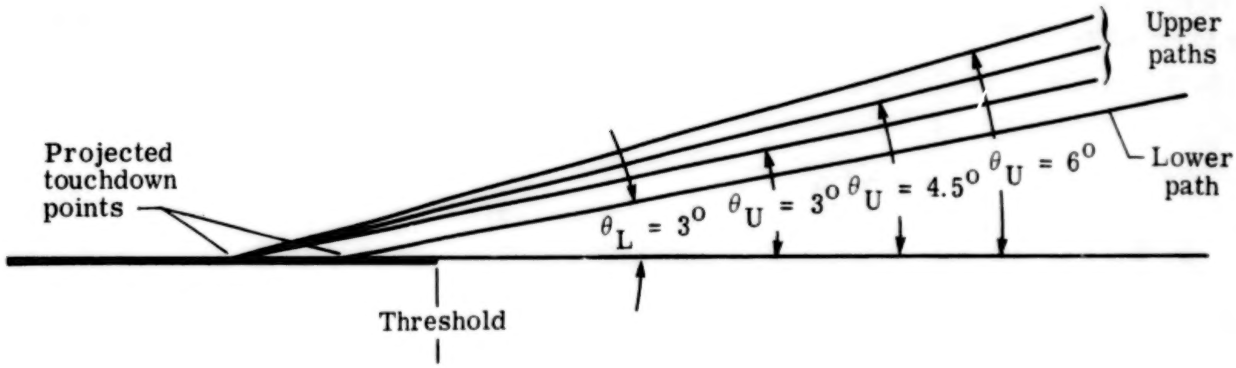


Figure 9.- Sketch illustrating three dual-path configurations analyzed.

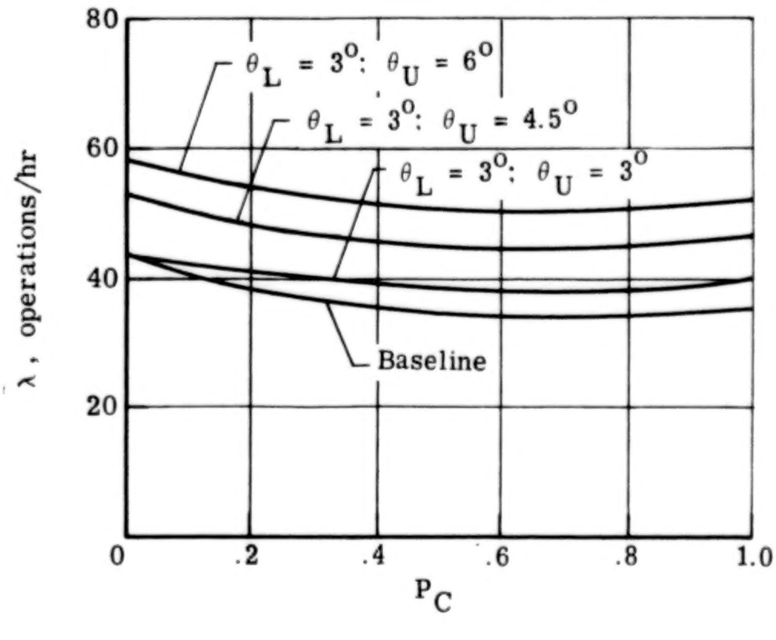


Figure 10.- Landing capacity for dual-path method using current separation intervals.

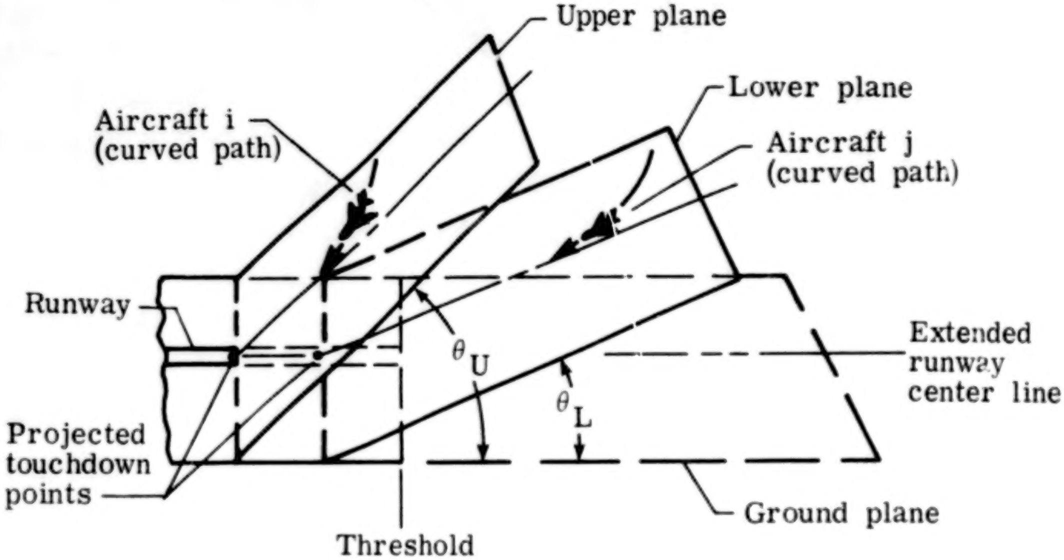


Figure 11.- Sketch illustrating dual-path-curved method.

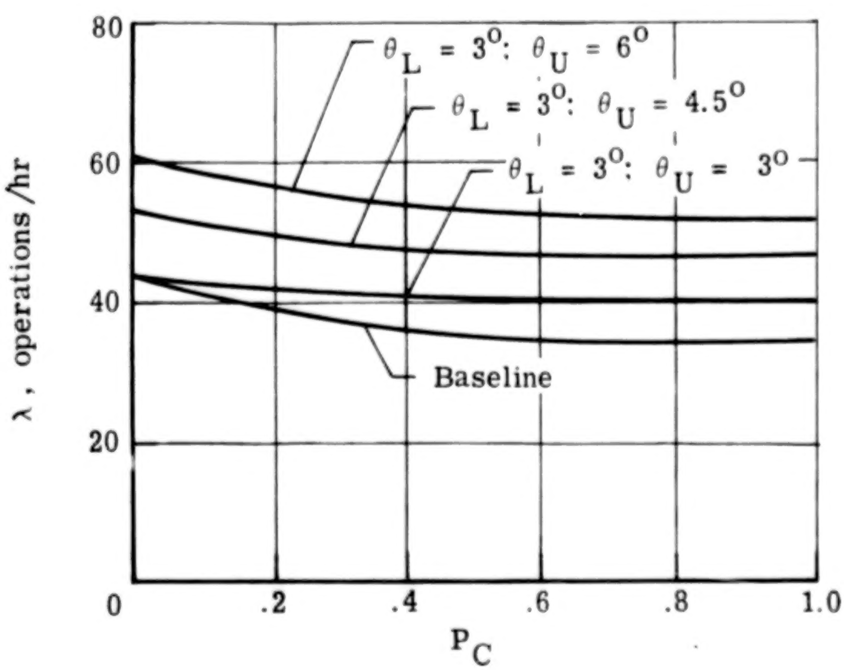


Figure 12.- Landing capacity for dual-path-curved method using current longitudinal separation intervals.

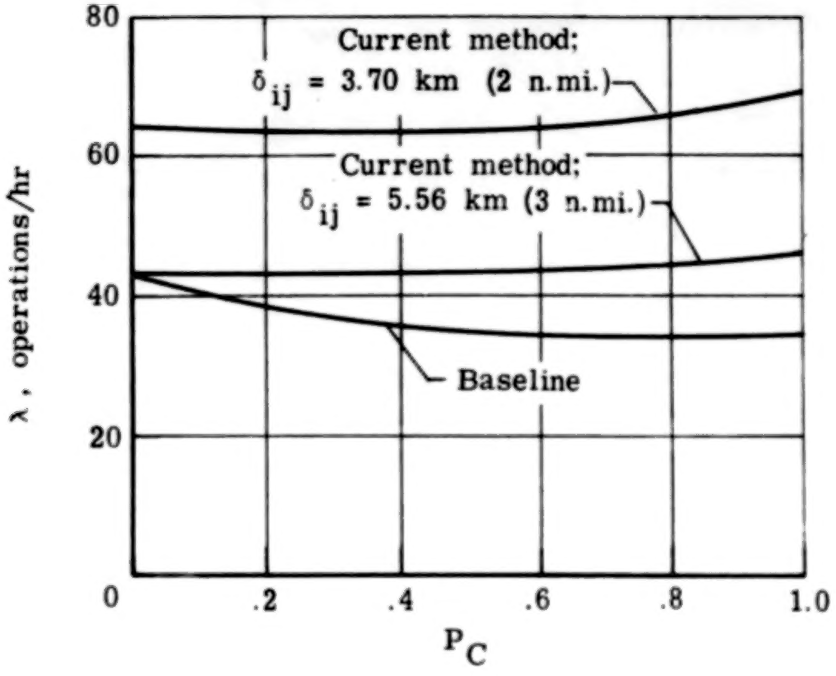


Figure 13.- Landing capacity for current method using reduced separation intervals.

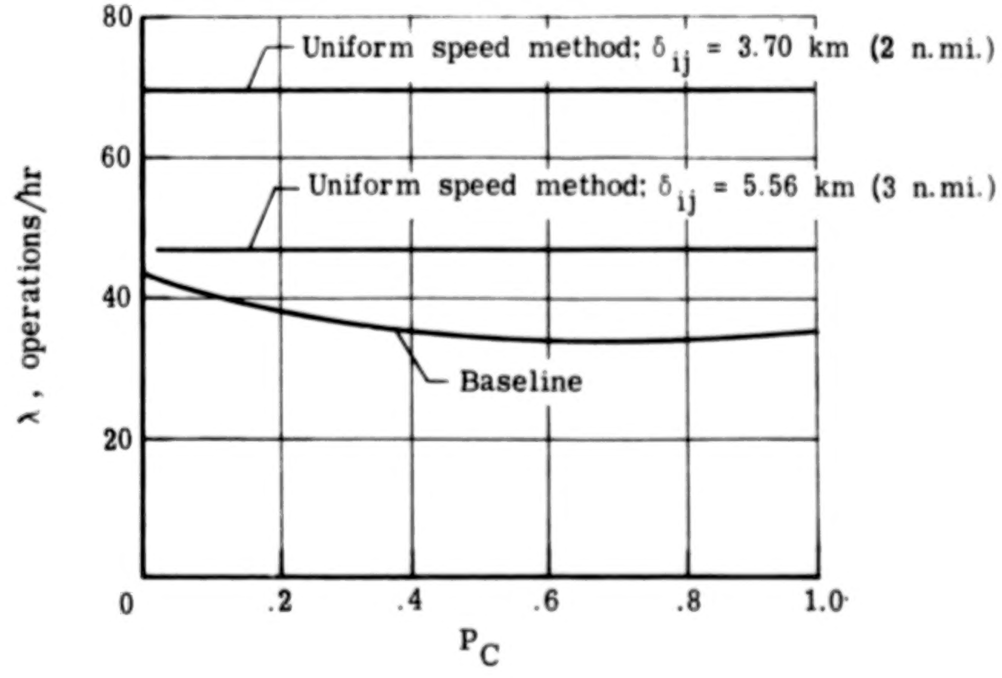


Figure 14.- Landing capacity for uniform speed method using reduced separation intervals.

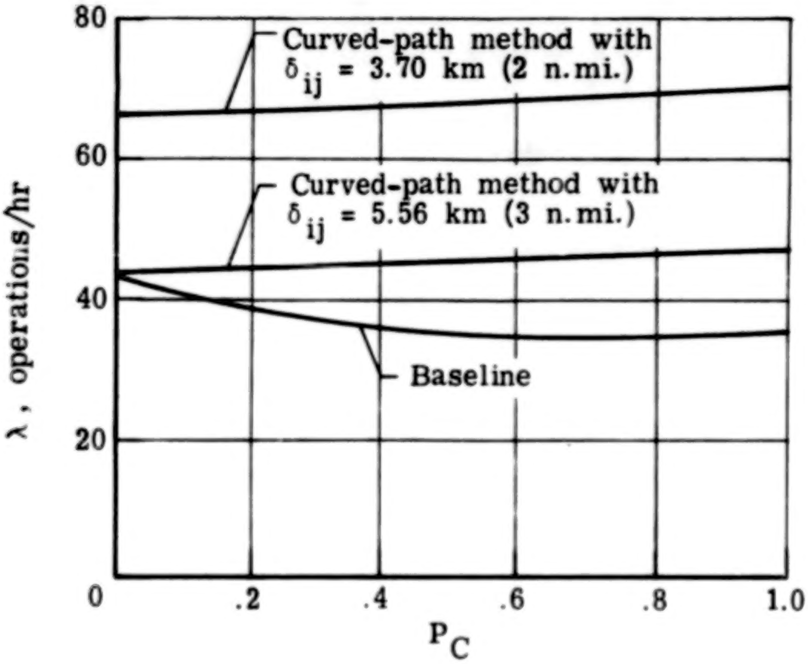


Figure 15.- Curved-path method with reduced separation intervals.

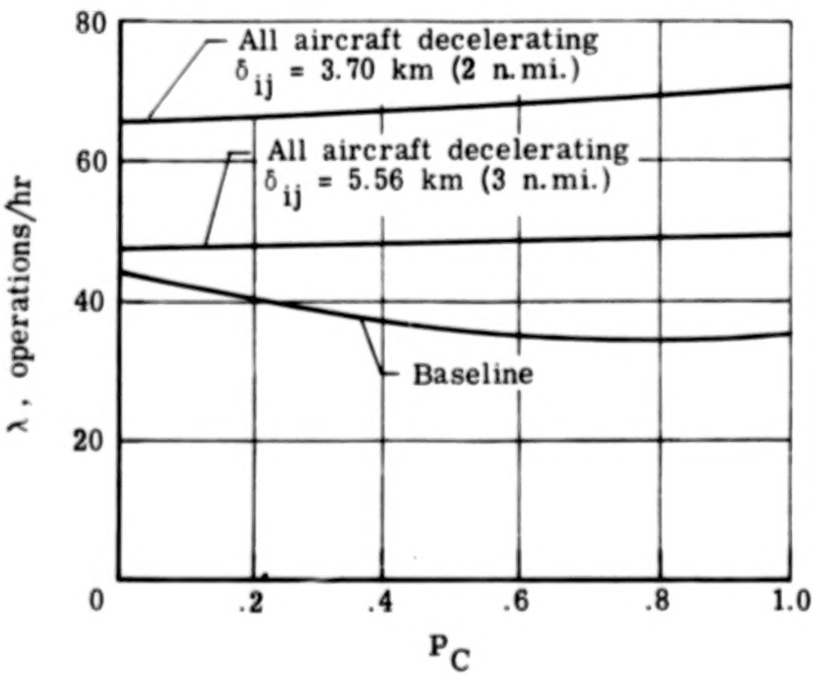


Figure 16.- Landing capacity for delayed flap method (all aircraft) using reduced separation intervals.

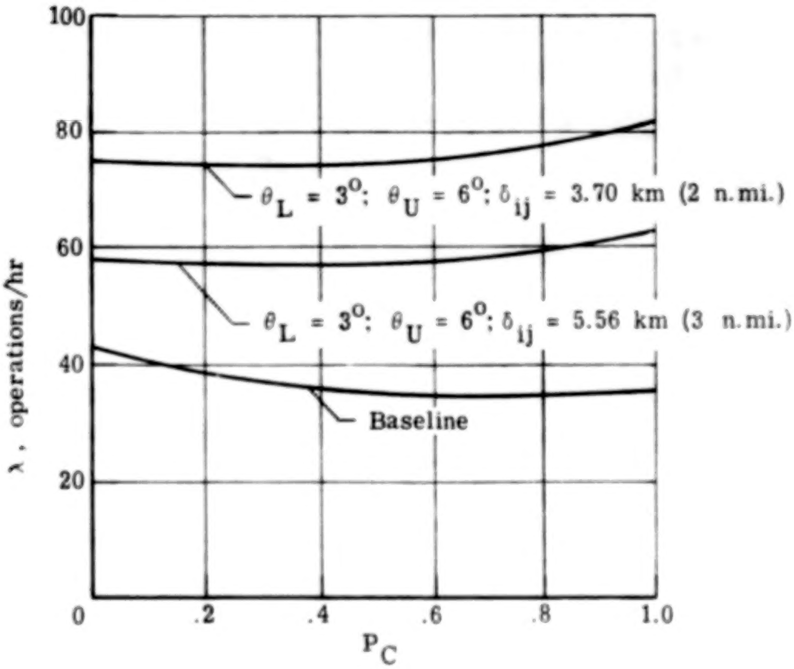


Figure 17.- Landing capacity for dual-path method using reduced separation intervals.

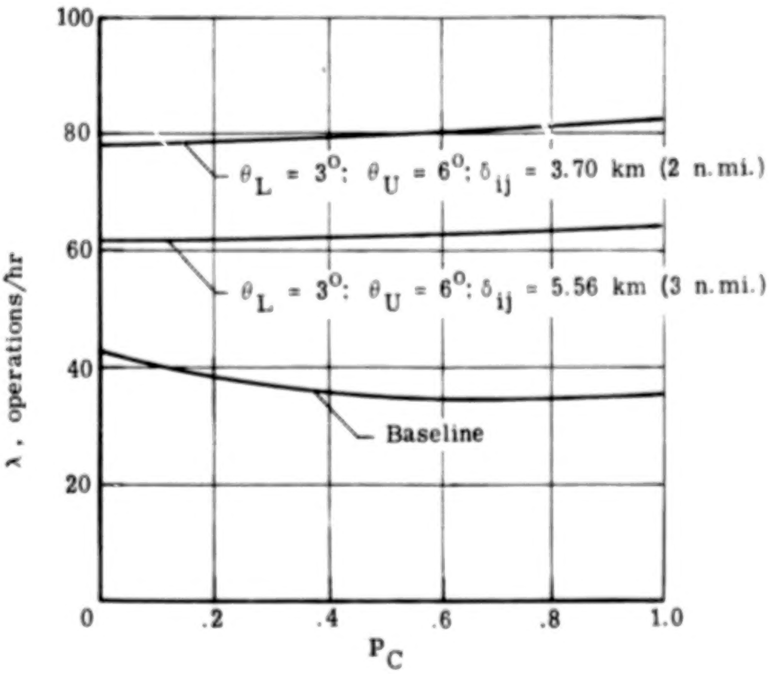


Figure 18.- Landing capacity for dual-path-curved method using reduced longitudinal separation intervals.

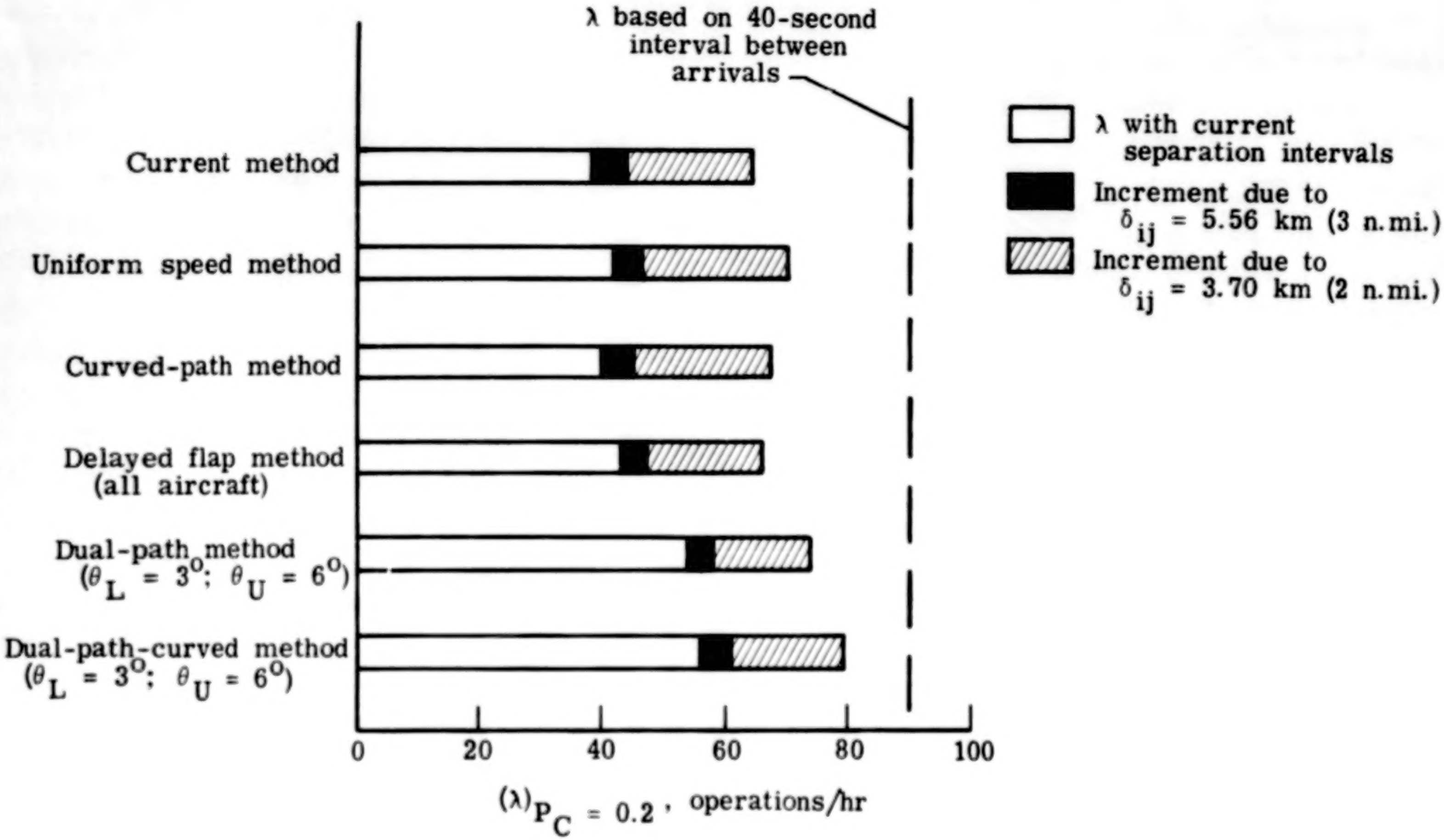


Figure 19.- Summary landing capacity data at $P_C = 0.2$.

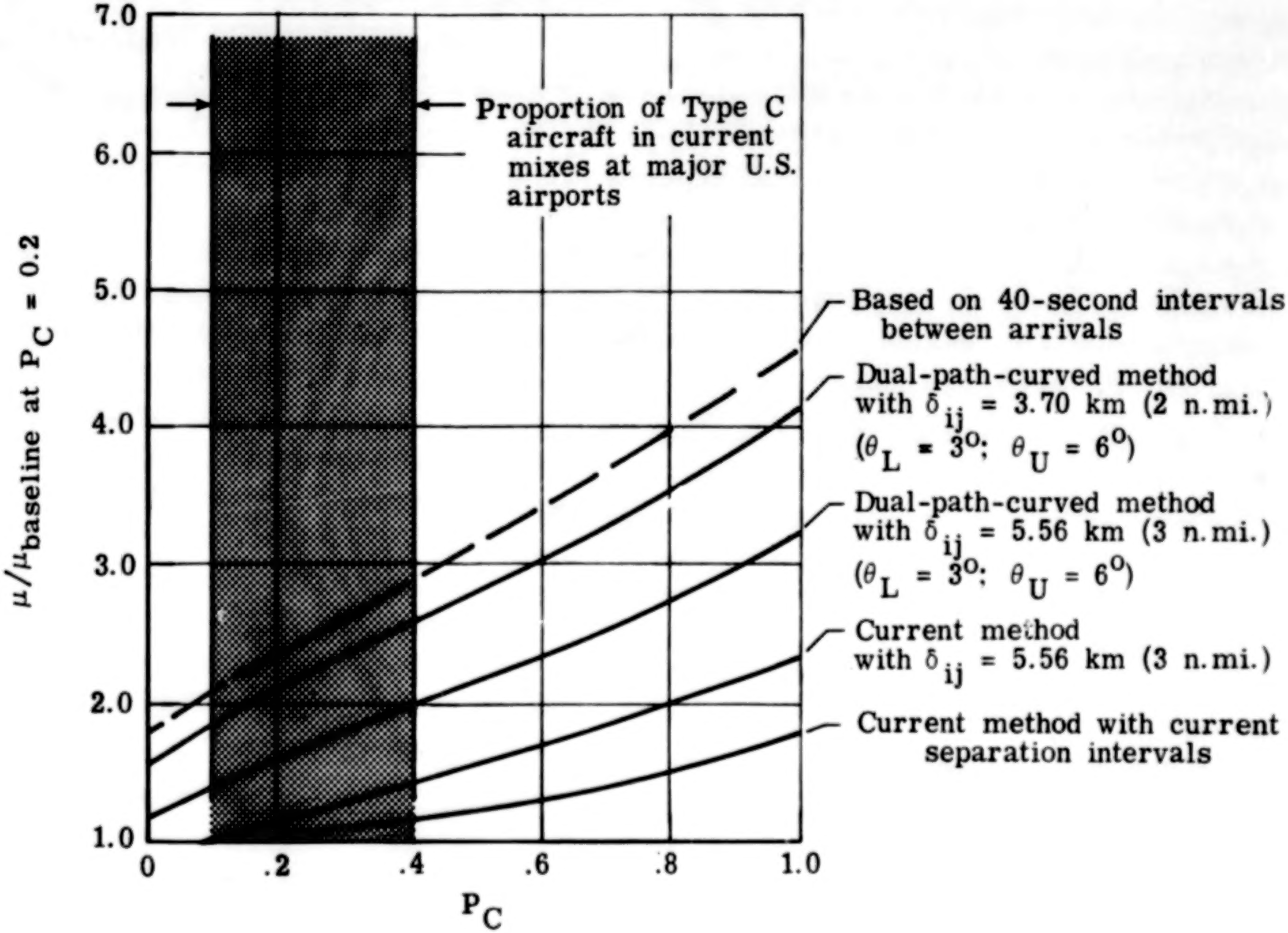


Figure 20.- Summary passenger delivery capacity (for 65 percent load factor) for several approach methods.

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15. Supplementary Notes

16. Abstract

A study of the effect of seven approach methods on the landing capacity of commercial jet transports was conducted. A dual-path approach concept, which offered vortex avoidance advantages, was found to provide significant gains with the current separation intervals. When this concept was combined with reduced intervals, the current landing capacity was approximately doubled. The anticipated increase in the demand for air transportation will require advanced approach methods, greatly reduced separation intervals, and larger proportions of high-passenger-capacity aircraft.

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